

Low-Frequency Spectral Turn-Overs in Millisecond Pulsars Studied from Imaging Observations

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ABSTRACT

Measurements of pulsar flux densities are of great importance for understanding the pulsar emission mechanism and for predictions of pulsar survey yields and the pulsar population at large. Typically these flux densities are determined from phase-averaged “pulse profiles”, but this method has limited applicability at low frequencies because the observed pulses can easily be spread out by interstellar effects like scattering or dispersion, leading to a non-pulsed continuum component that is necessarily ignored in this type of analysis. In particular for the class of the millisecond pulsars (MSPs) at frequencies below 200 MHz, such interstellar effects can seriously compromise detectability and measured flux densities. In this paper we investigate MSP spectra based on a complementary approach, namely through investigation of archival continuum imaging data. Even though these images lose sensitivity to pulsars since the on-pulse emission is averaged with off-pulse noise, they are insensitive to effects from scattering and provide a reliable way to determine the flux density and spectral indices of MSPs based on both pulsed and unpulsed components. Using the 74 MHz VLSSr as well as the 325 MHz WENSS and 1.4 GHz NVSS catalogues, we investigate the imaging flux densities of MSPs and evaluate the likelihood of spectral turn-overs in this population. We determine three new MSP spectral indices and identify six new MSPs with likely spectral turn-overs.

Key words: pulsars:general

1 INTRODUCTION

It is well established that there are two fundamental classes of pulsars: the normal (or “young”) pulsars, with spin periods between roughly a tenth of a second and a few seconds and spin-down rates between 10^{-18} and 10^{-12} s/s; and the class of the millisecond pulsars (MSPs), with spin periods below about 30 ms and spin-down rates below 10^{-17} s/s (Lee et al. 2012). According to standard theory, this latter group is created through a “recycling” process where a normal pulsar accretes mass from a main-sequence companion star through Roche-lobe overflow (Alpar et al. 1982). This accretion process increases the spin of the pulsar but also affects a variety of emission properties, as summarised by Kramer et al. (1998).

Studies of the spectral index of pulsars are of particular importance to any attempts at understanding the pulsar emission mechanism; and to clarify any differences between MSPs and their slower counterparts. Even though only few MSP spectra were available, previous work (Kramer et al. 1998; Toscano et al. 1998) found no significant difference between the spectral index distributions of MSPs and young pulsars, but Kramer et al. (1999) did find that MSP spectra tended to be somewhat less steep. Interestingly, recent simulations by Bates et al. (2013) indicate that spectral indices available for slow pulsars are biased towards steeper spectra because most pulsars with determined spectral indices were discovered in early, low-frequency surveys, which are most sensitive to steep-spectrum objects. Arguably the same bias does not exist for the MSPs, which were mostly discovered in 1.4-GHz surveys and are less biased to steep-spectrum sources. Clearly, a full comparison of the populations will

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require a significant increase in the number of spectral indices measured for MSPs.

While spectral indices provide the simplest description of a spectrum, some pulsar spectra display more complex features. Of specific interest to our discussion are the spectral turn-overs that have been observed in some pulsars at frequencies below 400 MHz (e.g. Sieber 1973; Kuzmin et al. 1978; Izvekova et al. 1981) and at frequencies near 1 GHz in a smaller sample (Maron et al. 2000).

Research into breaks in MSP spectra has been hampered by the small amount of data available; and inconsistencies in this limited data set. Erickson & Mahoney (1985) investigated the spectrum of the first known MSP (PSR J1939+2134 or B1937+21) and detected an indication of a possible turn-over in the spectrum below 75 MHz. Subsequently, Foster et al. (1991) observed a sample of four MSPs, including PSR J1939+2134, at a variety of frequencies and found no significant deviations from power-law spectra in any of these pulsars. McConnell et al. (1996) published the spectrum of the brightest MSP known, PSR J0437–4715 and found clear evidence for a spectral break around 200 MHz. This pulsar remained the only MSP with a clear spectral turn-over until Kuzmin & Losovsky (2001) published the largest sample so far, analysing the spectra of 30 MSPs at frequencies down to 100 MHz. Out of their large sample, only PSR J1012+5307 was found to have a turn-over in its spectrum. Most recently, observations of MSP J2145–0750 with the Long Wavelength Array in New Mexico (Ellingson et al. 2013) have shown very clear evidence of a flattening of the spectrum of this pulsar below a few hundred MHz (Dowell et al. 2013), suggesting that the non-detection of a break by Kuzmin & Losovsky (2001) was caused by a lack of measurement points and sizeable uncertainties on their measurements. This brings the total number of MSPs with suggested spectral breaks to four, out of a total sample of 33 MSPs with spectra down to ~ 100 MHz.

As this historical overview shows, the spectra of MSPs have only been investigated down to ~ 100 MHz on a small number of sources; and when additional data were added to previously published spectra, the results were contradicting as often as they were confirming. This illustrates how lack of sensitivity; lack of observations; and the lack of access to a truly wide frequency range have hampered this field.

One effect that limits the accessible frequency range in which pulsar flux density measurements can be made, lies in the way most of these observations are conducted. Typical pulsar observations are performed using the phase-folding technique, in which the incoming data are averaged as a function of pulse phase, given the known rotational period of the pulsar. This technique is normally advantageous because it separates the pulsed signal from the off-pulse noise and thereby gains significant sensitivity. However, when investigating flux density measurements, this phase-folding technique implicitly assumes that the off-pulse region (i.e. the phase-range where the pulsed emission reaches a minimum) only contains noise and no emission originating from the pulsar (Lorimer & Kramer 2005). This is not always true, because if a pulsar has only a small offset between its rotation axis and its magnetic axis, it is possible that the line of sight permanently crosses the polar emission region. In this case even the baseline level of the phase-folded profile would

contain emission that should be attributed to the pulsar, but which gets ignored as it is unpulsed.

At low frequencies this situation gets worse, since the pulsar emission is affected by a series of interstellar propagation effects that tend to smear out the emission over pulse phase (see Rickett 1977, for a review). Because dispersion can nowadays be corrected for through coherent dedispersion, the most important of these effects is scattering, which has approximately a $\nu^{-3.9}$ scaling (Bhat et al. 2004) and is therefore particularly relevant at the low frequencies where the spectral turn-overs are observed to occur.

An alternative approach to measuring spectra of MSPs is to determine the pulsar’s flux density from interferometric imaging. Since these maps are not phase-resolved they do tend to have less sensitivity, but in this way the *total* flux density can be determined¹ (including any potentially unpulsed component) and this flux density measurement is entirely insensitive to interstellar propagation delays like scattering. Moreover, several all-sky imaging surveys across a variety of observing frequencies have been released into the public domain, allowing spectrum investigations on a large sample of sources without any further requirement for observing time. Such imaging surveys were already used by Kaplan et al. (1998) who investigated pulsar flux densities and scintillation based on the 1.4 GHz NVSS (NRAO VLA Sky Survey) and the 325 MHz WENSS (Westerbork Northern Sky Survey), but they did not investigate these data for spectral breaks as they did not have access to a truly low-frequency survey.

Since the analysis by Kaplan et al. (1998), the known sample of pulsars has more than doubled, and with the recent publication of the improved 74 MHz VLSSr (VLA Low-Frequency Sky Survey Redux, Lane et al. 2012), the sensitivity of a similar investigation is significantly enhanced at the lower frequencies, providing significantly improved sensitivity to spectral breaks over an unprecedentedly large number of sources.

In this paper, we present the results from an investigation into spectral turn-overs in MSPs, based on the 74 MHz VLSSr, complemented with the 325 MHz WENSS and the 1.4 GHz NVSS. These three surveys are described in Section 2, along with the selected source sample. Section 3 lists our detections and the obtained spectra; and in Section 4 we summarise our findings.

2 IDENTIFICATION WITH APERTURE SYNTHESIS RADIO SURVEY IMAGES

In order to investigate the spectra of MSPs, we investigated the data from the three imaging surveys discussed below, for detections of MSPs. In this context we defined MSPs as being pulsars with spin periods below 30 ms and

¹ Note that phase-resolved measurements of flux density typically report the *phase averaged* flux density after subtracting a noise floor determined at off-pulse phases. This means that phase-resolved flux densities are directly comparable to interferometric flux density measurements. The only exception is the case where some part of the pulsar’s emission beam is continuously pointed towards us, as in this case only the pulsed fraction of the flux density is measured.

a time-derivative of the spin period $\dot{P} < 10^{-17} \text{s/s}^2$. We excluded pulsars in globular clusters to avoid obvious issues with confusion; and restricted our analysis to pulsars at declinations above -40° , as this is the lowest declination limit amongst the three surveys used. A list of candidate sources and their positions was taken from the ATNF pulsar catalogue³ (Manchester et al. 2005) and based on those positions the images from the three surveys were inspected for detections. In some cases the positions from the catalogue are referred to epochs that are up to a decade or more after the data for the surveys were taken. This could cause the pulsar position to have changed due to the high velocity of pulsars. However, based on proper motion measurements of the MSPs in our sample (where available) or the average transverse velocity of the pulsar population (which is less than 100 km/s, Hobbs et al. 2005), none of the MSPs in our sample was likely to have moved as much as a resolution element in any of the surveys used.

Identification of our candidate sources was done through queries of the available source catalogues⁴ and through visual inspection of the survey images, where a $3\text{-}\sigma$ detection threshold coincident with the catalogue position of the pulsar was required to claim a detection. For the sources below $\sim 5\sigma$ significance, which were not in the online catalogues, the position and flux density were subsequently determined through Gaussian fitting to the images. For all of our detections the offset between the fitted position and the most recent published position was well within the resolution of the images.

As mentioned, three imaging surveys were used. These were chosen based on their observing frequency, sensitivity and fraction of sky covered. The surveys used were:

VLSSr: The original Very Large Array (VLA) Low-Frequency Sky Survey (VLSS) and its catalogue were released in 2007 (Cohen et al. 2007). It covers 95% of the sky north of -30° declination at a frequency of 74 MHz with a resolution of approximately $80''$ and an RMS sensitivity of about 100 mJy/beam. The minimum integration time on each field is 75 minutes, consisting of three shorter observations, each approximately 25 minutes, separated in time by at least one hour. Following improvements in various data reduction algorithms (particularly related to bright-source peeling, radio frequency interference removal and ionospheric calibration) a renewed release of the survey and images was made in 2012 (Lane et al. 2012).

WENSS: The Westerbork Northern Sky Survey (WENSS), was performed with the Westerbork Synthesis Radio Telescope (WSRT), which consists of 14 parabolic antennas, between 1991 and 1996 at a frequency of 325 MHz, covering the entire sky north of declination $+28.5^\circ$ with a limiting $1\text{-}\sigma$ flux density of approximately 3.6 mJy. This survey has an

imaging resolution of $54'' \times 54'' / \sin(\delta)$ with δ the declination (Rengelink et al. 1997).

NVSS: The NRAO VLA Sky Survey (NVSS) was performed with the VLA at a frequency of 1.4 GHz with the compact D and DnC configurations during 1993 and 1996, with some additional observations carried out in 1997. The NVSS is a continuum survey covering the entire sky north of -40° declination with a FWHM angular resolution of $45''$ and $1\text{-}\sigma$ RMS flux density fluctuations of ≈ 0.45 mJy/beam (Condon et al. 1998).

3 RESULTS

According to the ATNF catalogue⁵, 130 sources satisfied the selection criteria laid out in Section 2. Out of these, we detected ten pulsars in the VLSSr data. A further six pulsars were expected to be detectable based on an extrapolation of the available higher-frequency data, but were not detected, providing strong evidence for a spectral break. The remaining 113 sources were not detected, but did not indicate a spectral turn-over. In some cases this was the case because their spectral index (as derived from higher-frequency data) is flat enough to make a non-detection at 74 MHz expected; while for other pulsars there are no flux density measurements at multiple frequencies available, making it impossible to derive a spectral index and therefore yielding no expected flux density at 74 MHz. The third and largest group (47 out of 113) were not detected because they lay outside the survey area, because the VLSSr data for them were corrupted, or because their positions are not known precisely enough to allow a confident identification.

In the following, we define the spectral index α as in

$$S(\nu) \propto \nu^\alpha, \quad (1)$$

with $S(\nu)$ the flux density at frequency ν . Since fitting non-linear functions in the presence of uncertainties is complicated and does not reliably quantify the often asymmetric uncertainties, we applied a Monte Carlo approach to the determination of our spectral indices. Practically this means we drew random realisations from the flux density measurements at all frequencies (using the published flux density values and interpreting the measurement uncertainties as Gaussian and symmetric). A power-law function (Equation 1) was then fitted to these simulated measurements through a linearised unweighted fit to determine realistic initial values which were used as the basis of a non-linear, weighted fit. The distribution of the slopes of these final fits (shown in figures 1, 2 and 4), then provided the most likely spectral index and its uncertainties.

In the cases where a spectral turn-over was required, this was always clear without requiring a spectral fit, i.e. no borderline cases were found. In these cases a separate spectral slope was fitted to the lowest- and highest-frequency measurements, up to a break frequency that was visually identified.

For the MSPs that were not detected in the VLSSr data, we used the same Monte Carlo approach on any available high-frequency data but extended the approach to provide

² We also considered pulsars with as-yet undetermined spindown \dot{P} , since these undetermined values are likely to be small.

³ Available at <http://www.atnf.csiro.au/research/pulsar/psrcat>.

⁴ The catalogue browsers for these surveys can be found at <http://www.cv.nrao.edu/vlss/VLSSlist.shtml>, <http://www.astron.nl/wow/testcode.php?survey=1> and <http://www.cv.nrao.edu/nvss/NVSSlist.shtml> respectively.

⁵ Version 1.50 of the ATNF catalogue, used on 25 July 2014.

Table 2. Summary of spectral index measurements. This table contains the spectral indices derived from the measurements in Table 1.

Pulsar name	Spectral index α	Turn-over frequency ν_{TO}	α below ν_{TO}
J0034–0534	-2.64 ± 0.05	–	–
J0218+4232	-2.41 ± 0.04	–	–
J1810+1744	$-2.57^{+0.14}_{-0.16}$	–	–
J1843–1113	-3.08 ± 0.10	–	–
J1903+0327	$-2.01^{+0.07}_{-0.05}$	–	–
J1939+2134	-2.59 ± 0.04	~ 74 MHz	$-1.94^{+0.06}_{-0.05}$
J1959+2048	$-2.79^{+0.08}_{-0.11}$	–	–
J2145–0750	-2.60 ± 0.04	~ 400 MHz	$-1.33^{+0.18}_{-0.17}$
J2215+5135	$-3.22^{+0.15}_{-0.23}$	–	–

a distribution of expected flux densities at an observing frequency of 74 MHz, assuming the power-law flux density scaling of Equation 1. This distribution was then compared to the $3\text{-}\sigma$ upper limit on the flux density from the VLSSr images to evaluate the likelihood of a spectral turn-over in these pulsars.

In the following sections, we discuss our detections and the non-detections that may indicate spectral turn-overs. Specifically, in Section 3.1 we discuss six detected MSPs that are consistent with previously published data; in Section 3.2 we present three detected MSPs that have their spectral index determined for the first time; and in Section 3.3 we discuss the six MSPs whose non-detections indicate likely spectral turn-overs.

3.1 Six MSPs Detected and Consistent with Previous Publications

In total, we detected 10 pulsars in the VLSSr. Four of these have no previous spectral index published and will therefore be discussed separately, in Section 3.2. The remaining six sources are all consistent with previously published spectral indices derived from higher-frequency data. Of these six, only PSR J0218+4232 was detected in the WENSS (the non-detections being primarily caused by the limited sky coverage of this survey) and the low luminosity of MSPs at higher frequencies made that only PSR J2145–0750 was detected in the NVSS. The list of the detected pulsars and all the flux density values used in our determination of spectral indices, is given in Table 1, the spectra of these pulsars are shown in Figure 1 and the derived spectral indices are given in Table 2. For a few sources a further discussion of our results is given below.

3.1.1 PSR J0034–0534

The spectral index of this pulsar has been measured twice before, by Toscano et al. (1998) who derived a spectral index of $\alpha = -2.6 \pm 1.0$ and subsequently by Kuzmin & Losovsky (2001) who found a slightly shallower spectrum with $\alpha = -2.3 \pm 0.3$. Our VLSSr detection lowers the lowest frequency in the spectrum from 111 MHz to 74 MHz and is in perfect agreement with the earlier Toscano et al. (1998) measurements, but in significant disagreement with the flux

density value of Kuzmin & Losovsky (2001). This disagreement indicates the Kuzmin & Losovsky (2001) flux density for this pulsar may have been underestimated. Excluding the Kuzmin & Losovsky (2001) value from our analysis, we derive a spectral index of $\alpha = -2.64 \pm 0.05$. We note furthermore that the folded pulse profile for this pulsar is very wide at these low frequencies⁶, making it possible that some component of unpulsed, scattered flux density was unaccounted for in the Kuzmin & Losovsky (2001) measurement.

3.1.2 PSR J0218+4232

Navarro et al. (1995) discovered PSR J0218+4232 and reported a significant fraction of its radio emission was not pulsed, implying it is an aligned rotator and causing an offset between its total flux density (as derived from imaging) and its pulsed flux density (as derived from phase-folded observations). Stairs et al. (1999) subsequently determined the magnetic inclination angle to be consistent with 0° , based on a fit of the rotating vector model (RVM, see Radhakrishnan & Cooke 1969) to observations at 410 and 610 MHz, thereby confirming the classification as an aligned rotator.

We detected PSR J0218+4232 in the VLSSr data with a flux density of 2.9 ± 0.4 Jy. In the WENSS, we detected the pulsar at 113 mJy. We did not find the pulsar in the NVSS, which may be explained by scintillation (Rickett 1977) since the survey’s 1.35 mJy $3\text{-}\sigma$ sensitivity is close to the 1.5 mJy published flux density at 1.4 GHz.

Combining our own measurements and those from Navarro et al. (1995) and Stairs et al. (1999) for both imaging and phase-folded cases, we find no evidence for a spectral turn-over and determine a spectral index $\alpha = -2.41 \pm 0.04$ for the total flux density, which is consistent with the spectral index for the phase-folded flux density: $\alpha = -2.32 \pm 0.09$, showing that the unpulsed flux density evolves consistently with the pulsed flux density (see Figure 1).

3.1.3 PSR J1939+2134

This pulsar was originally known as 4C21.53 and was detected in many aperture synthesis images before being uncovered as the first MSP (then known as PSR B1937+21, Backer et al. 1982). Consequently, its spectrum has been studied extensively, as can be seen from our summary in Figure 1, having flux density measurements from 4.8 GHz all the way down to 10 MHz. An initial controversy about the presence of a spectral turn-over could be explained by the very slight nature of the turn-over and the very low frequencies at which it occurs.

We detected PSR J1939+2134 in the VLSSr data with a flux density of 17.94 ± 2.15 Jy. This measurement is consistent with previously published flux density measurements and confirms the slight spectral turn-over first indicated by Erickson & Mahoney (1985). The WENSS did not cover this position and a confident detection in the NVSS was made impossible by a coincident extended source of emission slightly north of the pulsar position.

⁶ See, e.g. the European Pulsar Network Database at <http://www.jb.man.ac.uk/research/pulsar/Resources/epn/browser.html>.

Table 1. Summary of flux density measurements used. This table contains the flux densities used for our determination of spectral indices (summarised in Table 2), combining measurements from the VLSSr, WENSS and NVSS surveys with those already available from literature. In cases where the measurement uncertainty was not clear from the publication, we assumed a 30% uncertainty. These measurements are indicated by an asterisk.

Pulsar name	frequency (MHz)	flux density (mJy)	Reference and Notes
J0034–0534	74	1620 ± 210	This work.
	103	250 ± 120	Kuzmin & Losovsky (2001), significantly lower flux density, not used in fit
	436	17 ± 5	Toscano et al. (1998)
	660	5.5 ± 0.5	Toscano et al. (1998)
	1400	0.61 ± 0.09	Toscano et al. (1998)
	1660	0.56 ± 0.09	Toscano et al. (1998)
J0218+4232 (pulsed)	102	270 ± 150	Kuzmin & Losovsky (2001)
	410	$24 \pm 7^*$	Stairs et al. (1999)
	410	20 ± 10	Navarro et al. (1995)
	606	8 ± 5	Navarro et al. (1995)
	610	15 ± 7	Kramer et al. (1998)
	610	$11 \pm 3^*$	Stairs et al. (1999)
	1410	0.9 ± 0.2	Navarro et al. (1995)
	1410	0.9 ± 0.2	Kramer et al. (1998)
J0218+4232 (total)	34.5	$(4 \pm 1) \times 10^4$	Dwarakanath & Udaya Shankar (1990)
	74	2940 ± 360	This work.
	151	660 ± 330	Navarro et al. (1995)
	325	113 ± 4	This work.
	325	150 ± 50	Navarro et al. (1995)
	608	26 ± 7.8	Navarro et al. (1995)
	1400	1.5 ± 0.5	Navarro et al. (1995)
J1810+1744	74	1090 ± 150	This work.
	350	20 ± 4	Hessels et al. (2011)
J1816+4510	74	690 ± 110	This work.
J1843–1113	74	820 ± 194	This work.
	1400	0.10 ± 0.02	Hobbs et al. (2004)
J1903+0327	74	440 ± 100	This work.
	1400	1.3 ± 0.4	Champion et al. (2008)
	2000	0.62 ± 0.05	Champion et al. (2008)
	5000	0.09 ± 0.02	Champion et al. (2008)
J1939+2134 (B1937+21)	74	17940 ± 2150	This work.
	various	various	See Erickson & Mahoney (1985) for a complete listing
	700	63 ± 19	Manchester et al. (2013)
	1400	13 ± 5	Manchester et al. (2013)
	2695	2.0 ± 0.4	Kramer et al. (1999)
	3000	1.6 ± 0.7	Manchester et al. (2013)
	4850	1.0 ± 0.2	Kramer et al. (1999)
	8350	0.039 ± 0.015	Kowalińska et al. (2012)
J1959+2048 (B1957+20)	74	1880 ± 240	This work.
	318	60 ± 40	Fruchter et al. (1990) (retrieved from their Figure 2)
	430	26 ± 13	Fruchter et al. (1990) (retrieved from their Figure 2)
	606	8 ± 5	Fruchter et al. (1990) (retrieved from their Figure 2)
	1490	0.4 ± 0.2	Fruchter et al. (1990) (retrieved from their Figure 2)
	1400	0.4 ± 0.2	Kramer et al. (1998)

3.1.4 PSR J1959+2048

PSR J1959+2048 (also known as PSR B1957+20) is the first known eclipsing pulsar, discovered at 430 MHz by Fruchter et al. (1988). The eclipses occur when the pulsar passes behind its degenerate, $0.1-M_{\odot}$ companion, which is being ablated by the pulsar wind. At the discovery frequency, the pulsar is eclipsed $\sim 10\%$ of the time, but this eclipse fraction scales strongly with wavelength (Stappers et al. 2001).

We detected PSR J1959+2048 in the VLSSr data with a flux density of 1.88 ± 0.24 Jy. This area was not covered in the WENSS and we did not detect the pulsar in the NVSS

either, possibly due to eclipses. Our measurement extends the spectrum further down, indicating the absence of spectral breaks.

3.1.5 PSR J2145–0750

Dowell et al. (2013) recently observed PSR J2145–0750 with the Long Wavelength Array (LWA) in the frequency range 41 to 81 MHz. Combining their measurement with archival higher-frequency data, they fitted the pulsar’s spectrum to the following, somewhat unconventional, functional form:

Table 1 – *continued*

Pulsar name	frequency (MHz)	flux density (mJy)	Reference and Notes
J2145–0750	various	various	See Dowell et al. (2013).
	74	354 ± 91	This work.
	102	480 ± 120	Kuzmin & Losovsky (2001)
	102.5	90 ± 50	Malofeev et al. (2000)
	410	$46 \pm 14^*$	Stairs et al. (1999)
	430	$50 \pm 15^*$	Bailes et al. (1994)
	436	100 ± 30	Toscano et al. (1998)
	610	$19 \pm 6^*$	Stairs et al. (1999)
	660	36 ± 4	Toscano et al. (1998)
	700	16 ± 9	Manchester et al. (2013)
	1400	7 ± 0.9	Toscano et al. (1998)
	1400	2.6 ± 0.4	This work; significantly lower flux density, not used in fit
	1414	$6.6 \pm 2.0^*$	Stairs et al. (1999)
	1510	8 ± 2	Kramer et al. (1998)
	1520	$10 \pm 3^*$	Bailes et al. (1994)
	1660	5.4 ± 0.8	Toscano et al. (1998)
	2695	2.2 ± 0.5	Kramer et al. (1999)
	3100	1.4 ± 0.5	Manchester et al. (2013)
	4850	0.4 ± 0.1	Kramer et al. (1999)
	4850	0.44 ± 0.03	Kijak et al. (1997)
	8350	0.080 ± 0.037	Kowalińska et al. (2012)
J2215+5135	74	800 ± 120	This work.
	350	$5 \pm 1.5^*$	Hessels et al. (2011)

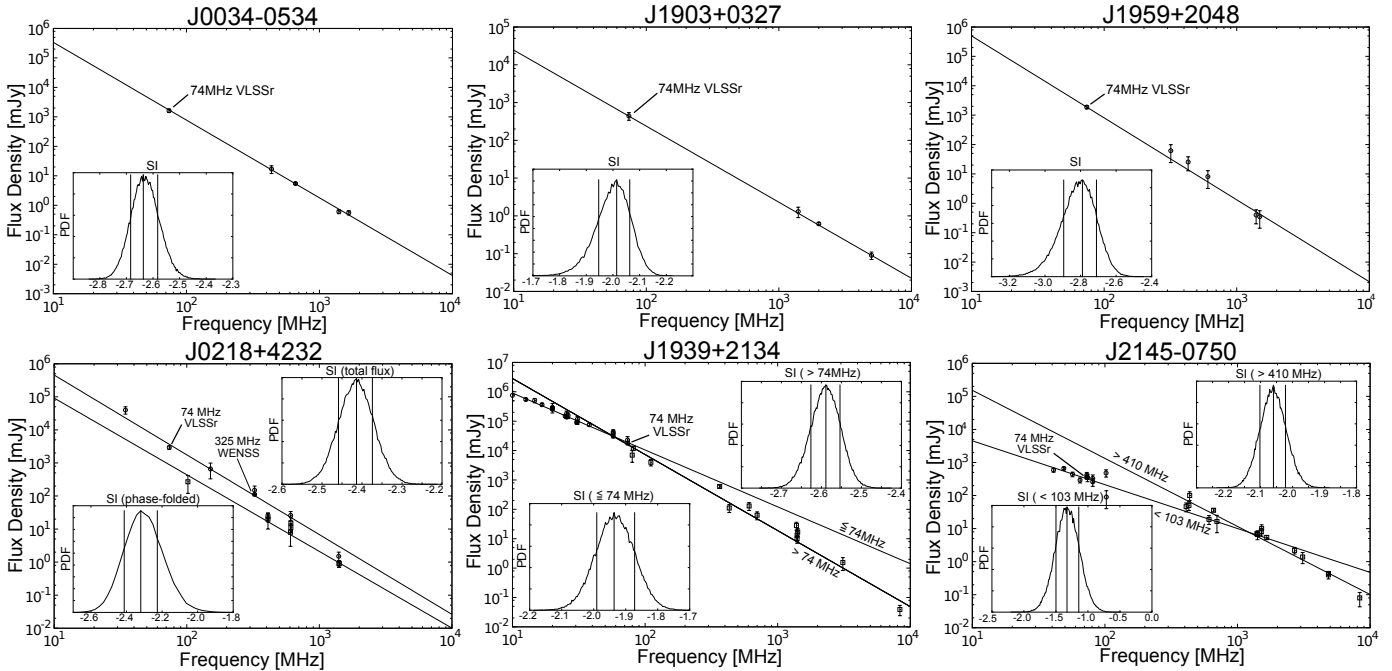


Figure 1. Spectra for the six detected pulsars with existing spectral information. Top row: spectra for three MSPs with no sign of a spectral break. Bottom row: spectra for the three MSPs with more complex spectra. The spectra for PSRs J1939+2134 and J2145–0750 show spectral turn-overs; and the spectrum for PSR J0218+4232 is consistent but at a higher level in imaging data than in phase-folded data as a consequence of the unpulsed emission (see Section 3.1.2 for details). The insets show the probability density functions for the spectral index distribution for each pulsar; in these insets the most likely spectral index and its 1- σ confidence interval are indicated by vertical bars. For the three pulsars on the bottom row, two different spectra were fitted. These two fits were based on the flux density measurements shown with dashed symbols; and flux density measurements shown in full symbols. In practice, for PSR J0218+4232, this means that dashed measurements are from phase-folded work, while the full markers indicate flux densities derived from imaging data.

$$S(\nu) = S_0 \left(\frac{\nu}{\nu_r} \right)^{m_1 + m_2 \log(\nu/\nu_r)} \quad (2)$$

with m_1 the spectral index at the lowest frequencies, m_2 the spectral curvature and ν_r the rollover frequency, which was relatively arbitrarily chosen by Dowell et al. (2013) to be about 730 MHz.

We detected PSR J2145–0750 in the VLSSr image with a flux density of 354 ± 91 mJy. This flux density measurement is consistent with the measurement by Dowell et al. (2013), who determined a flux density of $390 \pm 65 \pm 35$ mJy at 73 MHz, where the given uncertainties are for measurement noise and systematic uncertainties, respectively. We also detected this pulsar in the NVSS image, having a flux density of 2.6 mJy, which is significantly less than the 7.0 ± 0.9 mJy of Toscano et al. (1998). This discrepancy could be explained by scintillation, as indicated by the long-term monitoring of Manchester et al. (2013), who found the flux density of PSR J2145–0750 at 1.4 GHz to have an RMS scatter of no less than 12.5 mJy. The pulsar’s position was not included in the WENSS.

Because no flux density measurements are published for this pulsar between ~ 100 MHz and ~ 400 MHz, the exact break frequency is ill-determined (if there is indeed a particular break frequency rather than the continuous turn-over advocated by Dowell et al. 2013). Nevertheless, it is clear that at frequencies below 100 MHz the spectrum is flatter than above 400 MHz. Based on our own and the archival data listed above, we determine spectral indices of $-1.33^{+0.18}_{-0.17}$ and -2.60 ± 0.04 respectively.

3.2 Three New Spectral Indices

Four pulsars we detected in the VLSSr only had previous flux density measurements at a single frequency (or none at all), implying we were able to derive three spectral indices for the first time. These three spectra are shown in Figure 2 and the flux density measurements and spectral information are summarised in tables 1 and 2 respectively. Interestingly, two of the four pulsars in this class, PSRs J1810+1744 and J2215+5135 were found in a follow-up survey of unidentified γ -ray sources in the Fermi all-sky map (Hessels et al. 2011) and three out of four (PSRs J1810+1744, J1816+4510 and J2215+5135) inhabit eclipsing binary systems (Hessels et al. 2011; Kaplan et al. 2012). We cannot investigate possible spectral turn-overs for these pulsars, as we have less than three flux density measurements per pulsar. For PSR J1816+4510 specifically, we do not determine a spectral index either, as the only flux density measurements currently available are derived from uncalibrated survey observations and are therefore unreliable (see Stovall et al. 2014, and their Figure 6 in particular)⁷.

Finally, given their detections at low frequencies, these pulsars are by design biased towards steep spectral indices. The measured spectral indices are between $\alpha = -2.57$ and $\alpha = -3.22$, confirming that these pulsars constitute a particularly steep-spectrum part of the pulsar population: of the

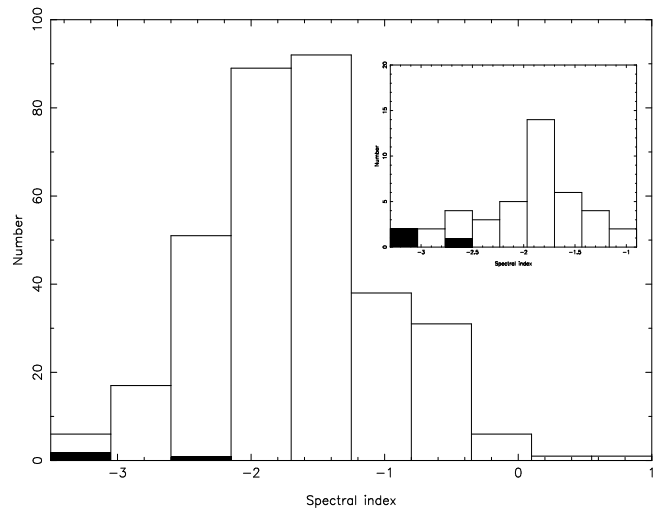


Figure 3. Histogram of all known pulsar spectral indices. The main figure shows all known spectral indices of pulsars, the inset shows the same plot for the class of the millisecond pulsars only. Our three new measurements are shown in black.

328 spectral indices available in the ATNF pulsar catalogue, only 9% have equally steep spectra as these three MSPs (see Figure 3).

3.3 Six MSPs with a High Probability of Spectral Turn-Over

Based on fluxes at higher frequencies (either available from literature, or derived from the NVSS or WENSS data), a spectral index can be derived and used to predict the flux at 74 MHz. For six undetected pulsars this predicted flux lay above the 3σ detection limit of the VLSSr. This may in some cases be explained by scintillation or because the higher-frequency flux density estimates could be unreliable (Levin et al. 2013). With the exception of those caveats, a non-detection can also imply a spectral turn-over. For these unexpectedly non-detected pulsars, we determined the probability of a spectral turn-over using the Monte Carlo approach outlined at the very start of this section. Table 3 provides the list of these pulsars, along with the spectral indices derived from the published flux densities and the likelihood of spectral turn-over following from our analysis. For PSR J1744–1134 we also used our NVSS detection at 3.5 ± 0.5 mJy. The spectra are shown in Figure 4.

4 CONCLUSIONS

There are two fundamentally different ways to determine pulsar flux densities. These are through observations averaged modulo the rotational period of the pulsar (“phase-folded” measurements); and through interferometric imaging observations. The former type has higher sensitivity because of the separation of pulsed signal and unpulsed noise, but the latter approach is unaffected by scattering in the interstellar medium (which especially affects low-frequency data) and does provide a correct measurement of the total pulsar flux density even in the case of aligned rotators, where only a part of the emission is pulsed.

⁷ If we were to use the Stovall et al. (2014) flux density values, an extreme spectral index of -3.76 would result, well in excess of the steepest pulsar spectral index currently published (-3.5 for PSR J0711+0931, Lommen et al. 2000).

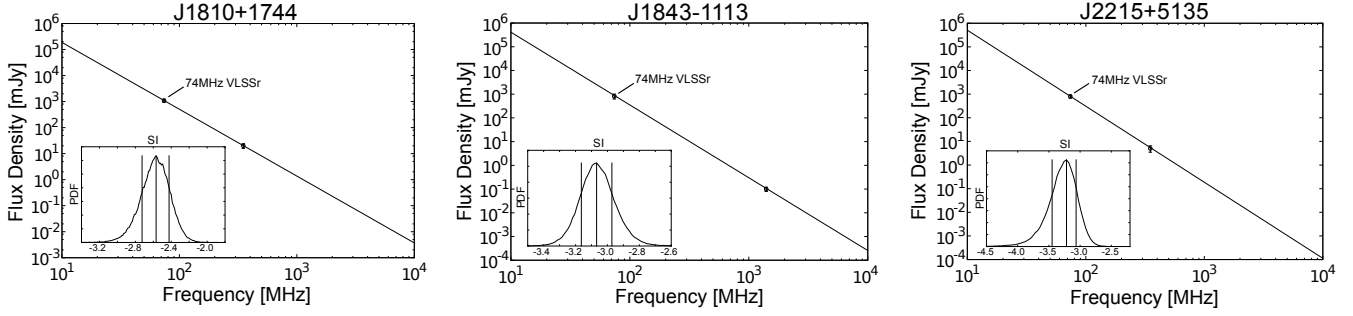


Figure 2. Three new MSP spectra obtained from our own imaging flux densities and published data. The inset panels show the likelihood distribution of the spectral indices, with the vertical lines indicating the most likely value and its 1- σ interval.

Table 3. Summary table for seven MSPs with a high probability of having a spectral break. Given are the pulsar name, the spectral index derived from previously published flux densities, the probability of turn-over and the literature references for the flux density measurements. Note these probabilities do not account for scintillation or underestimated uncertainties in the published measurements. References are as follows: (1) Kuzmin & Losovsky (2001); (2) Kramer et al. (1998); (3) Kramer et al. (1999); (4) Lorimer et al. (1995); (5) Toscano et al. (1998); (6) Manchester et al. (2013); (7) Stairs et al. (1999); (8) Lorimer et al. (1996); (9) Deneva et al. (2012); (10) Boriakoff et al. (1983); (11) Lommen et al. (2000); (12) Kaplan et al. (1998).

Pulsar name	Spectral index α	Turn-over likelihood	References
J0030+0451	$-2.14^{+0.25}_{-0.52}$	77%	1, 11
J1640+2224	$-2.18^{+0.12}_{-0.12}$	97%	1, 2, 3
J1643-1224	$-2.11^{+0.03}_{-0.04}$	100%	2, 3, 4, 5, 6, 12
J1744-1134	$-1.85^{+0.06}_{-0.06}$	100%	This work and 1, 2, 3, 5, 6, 7
J1911-1114	$-2.45^{+0.06}_{-0.05}$	100%	1, 2, 5, 7, 8
J1949+3106	$-3.18^{+0.24}_{-0.17}$	100%	This work and 9
J1955+2908	$-2.29^{+0.34}_{-0.25}$	82%	2 and 10

In this paper, we have used archival imaging data to determine the spectra of MSPs. We identified pulsars in the 1.4 GHz NVSS, the 325 MHz WENSS and, most importantly, the 74 MHz VLSSr. The VLSSr is of particular importance because it extends the investigated spectra to the lower frequencies, where phase-folded observations are often hampered by scattering effects and where investigation of potential spectral turn-overs becomes possible.

We only obtained a few detections in the NVSS, mostly because of the limited sensitivity of this survey compared to the low flux densities of MSPs at 1.4 GHz. In the WENSS our detection rate was lowered by the survey's limited sky coverage. The VLSSr did yield ten new pulsar flux density measurements; and for six sources a non-detection in the VLSSr provided significant evidence for spectral turn-overs at lower frequencies. Such evidence is hard to obtain from phase-folded observations since those cannot distinguish between pulsars that are too weak to be detected and pulsars that are bright but heavily scattered.

In total, we extended the spectra of 16 pulsars to frequencies below 100 MHz and found evidence for turn-overs in eight of these. Five of the eight pulsars with spectral turn-overs were previously reported to not have a spectral turn-over, based on higher-frequency data of Kuzmin & Losovsky (2001), suggesting in these cases the turn-over occurs near or just below 100 MHz. Following our work, a total of 39 MSPs have had their spectra investigated at frequencies down to or

below 100 MHz; and 10 out of those show evidence for turn-overs – a much higher fraction than previously thought.

The largest analysis of spectra for young pulsars to date, was published by Maron et al. (2000). They found there were two separate populations of pulsars with spectral breaks. About 10% of the population displayed spectral steepening at frequencies around or above 1.4 GHz, whereas a far smaller number of pulsars (on the order of a percent) showed spectral turn-overs at frequencies around 100 MHz. The frequencies of the spectral turn-overs found in our sample are comparable to the latter, low-frequency turn-over sub-population. The fraction of the population displaying turn-overs (about one in four), however, is similar to the fraction of young pulsars showing high-frequency turn-overs ($\sim 10\%$). This lends some credence to the postulate that MSP spectra are fundamentally identical to the spectra of young pulsars, albeit shifted to lower frequencies, as first proposed by (Kramer et al. 1999).

Future complements to our work will be provided by a host of new SKA pathfinder arrays that operate at the lowest frequencies continuously observable from Earth. All three of these pathfinders (LOFAR, LWA, MWA) are now capable of performing phase-resolved pulsar observations (Stappers et al. 2011; Dowell et al. 2013; Bhat et al. 2014) and will therefore carry spectral investigations to lower frequencies, even for fainter pulsars that are undetectable in most imaging surveys. Furthermore, all-sky surveys by these three telescopes, combined with phase-resolved observations may

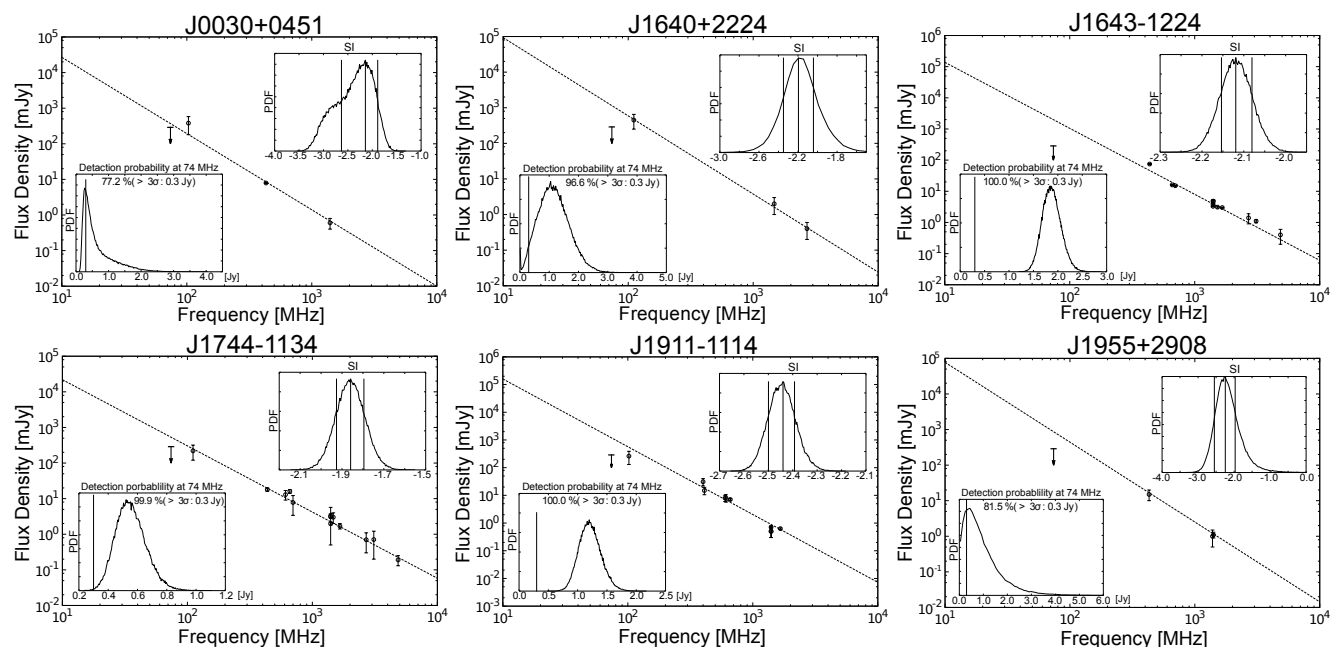


Figure 4. Spectra for six MSPs with a high probability of having a spectral turn-over. The arrows indicate the $3\text{-}\sigma$ upper limits in the 74 MHz VLSSr maps. The insets in the top-right of each sub-figure show the probability distribution of the spectral index based on the higher-frequency data referenced in Table 3; while the inset in the lower-left of each sub-figure shows the probability density function of the 74 MHz flux density based on this distribution of spectral indices, along with the detection probability at 74 MHz assuming the spectrum does not have a spectral break. The vertical lines in the top-right plot show the most likely spectral index value along with its $1\text{-}\sigma$ uncertainty interval; the vertical line in the lower-left plot shows the $3\text{-}\sigma$ detection limit of the VLSSr (approximately 300 mJy).

shed some light on the prevalence and strength of interstellar scattering in the sample of MSPs that are undetectable in phase-resolved observations.

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⁸ <http://www.cv.nrao.edu/vlss/>

⁹ <http://www.cv.nrao.edu/nvss/>

¹⁰ <http://www.astron.nl/wow/testcode.php?survey=1>

REFERENCES

- Alpar M. A., Cheng A. F., Ruderman M. A., Shaham J., 1982, *Nature*, 300, 728
- Backer D. C., Kulkarni S. R., Heiles C., Davis M. M., Goss W. M., 1982, *Nature*, 300, 615
- Bailes M., Harrison P. A., Lorimer D. R., Johnston S., Lyne A. G., Manchester R. N., D’Amico N., Nicastro L., Tauris T. M., Robinson C., 1994, *ApJ*, 425, L41
- Bates S. D., Lorimer D. R., Verbiest J. P. W., 2013, *MNRAS*, 431, 1352
- Bhat N. D. R., Cordes J. M., Camilo F., Nice D. J., Lorimer D. R., 2004, *ApJ*, 605, 759
- Bhat N. D. R., Ord S. M., Tremblay S. E., Tingay S. J., Deshpande A., van Straten W., Oronsaye S., Bernardi G., et al., 2014, *ArXiv e-prints*
- Boriakoff V., Bucceri R., Fauci F., 1983, *Nature*, 304, 417
- Champion D. J., Ransom S. M., Lazarus P., Camilo F., Bassa C., Kaspi V. M., Nice D. J., Freire P. C. C., Stairs I. H., et al., 2008, *Science*, 320, 1309
- Cohen A. S., Lane W. M., Cotton W. D., Kassim N. E., Lazio T. J. W., Perley R. A., Condon J. J., Erickson W. C., 2007, *AJ*, 134, 1245
- Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, *AJ*, 115, 1693
- Deneva J. S., Freire P. C. C., Cordes J. M., Lyne A. G., Ransom S. M., Cognard I., Camilo F., Nice D. J., Stairs I. H., et al., 2012, *ApJ*, 757, 89
- Dowell J., Ray P. S., Taylor G. B., Blythe J. N., Clarke T., Craig J., Ellingson S. W., Helmboldt J. F., Henning P. A., Lazio T. J. W., Schinzel F., Stovall K., Wolfe C. N., 2013,

- ApJ, 775, L28
- Dwarakanath K. S., Udaya Shankar N., 1990, *Journal of Astrophysics and Astronomy*, 11, 323
- Ellingson S. W., Taylor G. B., Craig J., Hartman J., Dowell J., Wolfe C. N., Clarke T. E., Hicks B. C., Kassim N. E., Ray P. S., Rickard L. J., Schinzel F. K., Weiler K. W., 2013, *IEEE Transactions on Antennas and Propagation*, 61, 2540
- Erickson W., Mahoney M., 1985, ApJ, 299, L29
- Foster R. S., Fairhead L., Backer D. C., 1991, ApJ, 378, 687
- Fruchter A. S., Berman G., Bower G., Convery M., Goss W. M., Hankins T. H., Klein J. R., Nice D. J., Ryba M. F., Stinebring D. R., Taylor J. H., Thorsett S. E., Weisberg J. M., 1990, ApJ, 351, 642
- Fruchter A. S., Stinebring D. R., Taylor J. H., 1988, *Nature*, 333, 237
- Hessels J. W. T., Roberts M. S. E., McLaughlin M. A., Ray P. S., Bangale P., Ransom S. M., Kerr M., Camilo F., Decesar M. E., 2011, in Burgay M., D'Amico N., Esposito P., Pellizzoni A., Possenti A., eds, *American Institute of Physics Conference Series Vol. 1357 of American Institute of Physics Conference Series, A 350-MHz GBT Survey of 50 Faint Fermi γ -ray Sources for Radio Millisecond Pulsars*. pp 40–43
- Hobbs G., Faulkner A., Stairs I. H., Camilo F., Manchester R. N., Lyne A. G., Kramer M., D'Amico N., Kaspi V. M., Possenti A., McLaughlin M. A., Lorimer D. R., Burgay M., Joshi B. C., Crawford F., 2004, MNRAS, 352, 1439
- Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, MNRAS, 360, 974
- Izvekova V. A., Kuz'min A. D., Malofeev V. M., Shitov Y. P., 1981, *Astrophys. Space Sci.*, 78, 45
- Kaplan D. L., Condon J. J., Arzoumanian Z., Cordes J. M., 1998, ApJS, 119, 75
- Kaplan D. L., Stovall K., Ransom S. M., Roberts M. S. E., Kotulla R., Archibald A. M., Biwer C. M., Boyles J., Dartez L., et al., 2012, ApJ, 753, 174
- Kijak J., Kramer M., Wielebinski R., Jessner A., 1997, A&A, 318, L63
- Kowalińska M., Kijak J., Maron O., Jessner A., 2012, in Lewandowski W., Maron O., Kijak J., eds, *Electromagnetic Radiation from Pulsars and Magnetars Vol. 466 of Astronomical Society of the Pacific Conference Series, Observations of Millisecond Pulsars at 8.35 GHz*. p. 101
- Kramer M., Lange C., Lorimer D. R., Backer D. C., Xilouris K. M., Jessner A., Wielebinski R., 1999, ApJ, 526, 957
- Kramer M., Xilouris K. M., Lorimer D. R., Doroshenko O., Jessner A., Wielebinski R., Wolszczan A., Camilo F., 1998, ApJ, 501, 270
- Kuzmin A. D., Losovsky B. Y., 2001, A&A, 368, 230
- Kuzmin A. D., Malofeev V. M., Shitov Y. P., Davies J. G., Lyne A. G., Rowson B., 1978, MNRAS, 185, 441
- Lane W. M., Cotton W. D., Helmboldt J. F., Kassim N. E., 2012, *Radio Science*, 47, 0
- Lee K. J., Guillemot L., Yue Y. L., Kramer M., Champion D. J., 2012, MNRAS, 424, 2832
- Levin L., Bailes M., Barsdell B. R., Bates S. D., Bhat N. D. R., Burgay M., et al., 2013, MNRAS, 434, 1387
- Lommen A. N., Zepka A., Backer D. C., McLaughlin M., Cordes J. M., Arzoumanian Z., Xilouris K., 2000, ApJ, 545, 1007
- Lorimer D. R., Kramer M., 2005, *Handbook of Pulsar Astronomy*. Cambridge University Press
- Lorimer D. R., Lyne A. G., Bailes M., Manchester R. N., D'Amico N., Stappers B. W., Johnston S., Camilo F., 1996, MNRAS, 283, 1383
- Lorimer D. R., Nicastrò L., Lyne A. G., Bailes M., Manchester R. N., Johnston S., Bell J. F., D'Amico N., Harrison P. A., 1995, ApJ, 439, 933
- McConnell D., Ables J. G., Bailes M., Erickson W. C., 1996, MNRAS, 280, 331
- Malofeev V. M., Malov O. I., Shchegoleva N. V., 2000, *Astronomy Reports*, 44, 436
- Manchester R. N., Hobbs G., Bailes M., Coles W. A., van Straten W., Keith M. J., et al., 2013, PASA, 30, 17
- Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, AJ, 129, 1993
- Maron O., Kijak J., Kramer M., Wielebinski R., 2000, in Kramer M., Wex N., Wielebinski R., eds, *Pulsar Astronomy - 2000 and Beyond, IAU Colloquium 177 Pulsar spectra analysis*. Astronomical Society of the Pacific, San Francisco, pp 227–228
- Maron O., Kijak J., Kramer M., Wielebinski R., 2000, A&AS, 147, 195
- Navarro J., de Bruyn G., Frail D., Kulkarni S. R., Lyne A. G., 1995, ApJ, 455, L55
- Radhakrishnan V., Cooke D. J., 1969, *Astrophys. Lett.*, 3, 225
- Rengelink R. B., Tang Y., de Bruyn A. G., Miley G. K., Bremer M. N., Roettgering H. J. A., Bremer M. A. R., 1997, A&AS, 124, 259
- Rickett B. J., 1977, *Ann. Rev. Astr. Ap.*, 15, 479
- Sieber W., 1973, A&A, 28, 237
- Stairs I. H., Thorsett S. E., Camilo F., 1999, ApJS, 123, 627
- Stappers B. W., Bailes M., Lyne A. G., Camilo F., Manchester R. N., Sandhu J. S., Toscano M., Bell J. F., 2001, MNRAS, 321, 576
- Stappers B. W., Hessels J. W. T., Alexov A., Anderson K., Coenen T., et al., 2011, A&A, 530, A80
- Stovall K., Lynch R. S., Ransom S. M., Archibald A. M., et al., 2014, ApJ, 791, 67
- Toscano M., Bailes M., Manchester R., Sandhu J., 1998, ApJ, 506, 863